Source Finiteness, Signal Decorrelation, Spectral Scalloping and Identification of Multiple Delayed Explosions.

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ABSTRACT.

Our results show that a generalized model that includes propagation delays and signal decorrelation can reproduce numerous observed features in the spectral modulation patterns of regional phases from quarry blasts. Analyses of spectra associated with various regional arrivals of the same event revealed differences in modulation strength and apparent shifts in modulation patterns These may be associated with source finiteness, propagation delays and signal decorrelation. Potentially these features can be used to derive information with regards to the spatial extent and layout of shot arrays. Modulation patterns or the locations of first minima in the spectra are generally not determined solely by the time duration of the shot sequences as often claimed, but are complex functions of numerous factors. Lack of spectral modulation does not necessarily indicate a single explosion or the absence of ripple firing either. Since this project has just begun, the results presented here are relevant only a to a subset of the tasks to be performed under this contract.

Key Words

Discrimination

Mining practices

Quarry blasts

Seismic sources

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OBJECTIVES.

The objective of this project is the implementation of various advanced time series processing techniques for small array data and their implementation in Geotool and, ultimately, various AFTAC systems for seismic monitoring. The project includes the implementation of site-specific automatic phase recognition algorithms, signal enhancement methods, and deconvolution algorithms combined with signal complexity discrimination.

RESEARCH ACCOMPLISHED.

Spectral modulation (scalloping) is an effective discriminant for distinguishing ordinary ripple-fired quarry blasts from large, single explosions and earthquakes. It cannot be used, however, to distinguish between single chemical explosions and small nuclear blasts, neither can it be used discriminate between ripple-fired quarry blasts and multiple large explosions, some of which could be nuclear. Thus as a discriminant, scalloping has limitations. Nevertheless spectral scalloping can provide information about the spatio-temporal structure of sources.

Data Analyses.

The regional phase spectra presented in this paper were produced by a uniform procedure. For a given event all traces were inspected and only the sensor outputs with uncompromised data quality were kept. All events analyzed also had very high signal-to-noise ratios with the even weakest arrivals (such as Pn), high above the background noise level. The various regional arrivals were windowed using the same chosen window length of 12.8 seconds for each type of arrival. The Parzen tapering function was used on each window which heavily tapered off both ends of each window. The position of the windows were chosen such that the arrival to be analyzed was close to the center of the window in order avoid reduction of its amplitude by the taper. After Fourier transforming and squaring the amplitude spectra of each sensor for a given arrival the resulting power spectra were smoothed by a 5 point moving average and averaged over all the chosen sensors of the array.

The most common modulation pattern observed in regional seismograms is nearly identical for the various phases in the seismogram (**Figure 1**). Such modulations can be easily seen in spectra computed for various time windows or continuous sonograms. When the causative time patterns of shots are simple, such as a pair of collocated explosions, we also can discern the time pattern in cepstral analyses. In some seismograms there are some finer observable spectral features that can be explained by source finiteness effects. These observable effects include phase-velocity dependent frequency shifts (or rescaling) in the spectral modulation patterns (**Figure 2**) and differences in the degree of modulation for the various regional seismic arrivals (**Figure 3**).

Theoretical Modelling of Spectral Modulation.

A common assumption made in various studies of spectral modulation is that the modulation patterns, especially the frequency of the first spectral minimum, are simple functions of source duration, i.e. the time length of the shot sequence. It is easy to show that this is not the case. The time delays between shots at quarries are generally much shorter than the digitizing time interval at most sensors of regional arrays (25 msec). Thus the arrays essentially "see" a simplified time function which can be derived by smoothing the original time sequence with a sinc function and resampling it at a 25 msec sampling rate. One can easily verify that this procedure does not change the resulting spectra below the Nyquist frequency of 20 Hz. By generating shot time sequences that have the same duration but have different variations in charge sizes with time we show that the locations of the first spectral minimum can be shifted significantly. It is also easy to design ripple firing sequences with approximately Gaussian envelopes when smoothed and resampled at 40 Hz that would not display any modulation despite their finite duration. Thus the spectral modulation patterns are not simple functions of duration.

Obviously the model of linear superposition of shots with identical waveforms cannot fully explain the observations of differences in modulation of the various regional arrivals presented above. What is needed is a model that incorporates the effects of signal decorrelation and propagation delays. Descriptions of firing practices at some mines indicate the use of very large shot arrays with dimensions close to a kilometer and firing time delays of the order of seconds (Kim et al 1994). When a shot array is even moderately large, for instance, when its dimensions are of the order of hundreds of meters we can no longer assume that the waveforms of two widely separated shots are the same. The waveforms originated by the various charges are bound to be decorrelated, by invoking reciprocity arguments, in a way similar to waveform decorrelation observed at small arrays. The frequency-limited correlation coefficients (coherences) of waveforms at small arrays were found to be approximately exponentially dependent on the product of distance between two observation points and frequency.

Analyses of waveform decorrelation at NORESS indicated that the waveform decorrelation is stronger for for phases with low propagation velocities such as Sn and Lg compared to fast travelling phases such as Pn and Pg. The stronger decorrelation for Sn and Lg may also be related to the more complex mode-ray structures of these phases (Der and Baumgardt 1994). There are also indications that the rate of decorrelation may depend on the direction of the wave propagation relative to the direction chosen in the horizontal plane (Der et al 1988). For simplicity in this paper we shall ignore this directionality and will assume a decorrelation factor proportional to $exp(-\alpha fd)$, where α is a constant determining the rate of decorrelation f is frequency and d is the intersensor diatance. The rate of waveform decorrelation will obviously depend on the degree of heterogeneities in the local structure and path and thus will vary from place to place. The second factor that must be considered for large shot arrays is the propagation delay between pairs of charges which for shot patterns of the order of hundreds of meters are not negligible compared to the absolute time lags among shots. These delays will be added to the absolute time differences and produce essentially a Doppler effect. For nonsymmetrical space-time distributions of shots thus will give a directional dependence to the spectra of quarry blasts observed. Moreover, since the additive relative propagation delays depend on the dominant phase veocity of each arrival, the spectral modulations will not be the same for all phases. The formula that approximately describes the observed power spectra including all these factors is

$$Y(\omega) = \sum_{i=1}^{N} |X_i(\omega)|^2 + 2 \sum_{j=1}^{N} \sum_{k=j+1}^{N} |X_j(\omega) X_k(\omega) C(\omega,\Delta_{jk})| \cos \omega (\tau_j - \tau_k + d_{jk}) \tag{1}$$

where the factor $C(\omega,\Delta)$ is the coherence between two waveforms corresponding to the angular frequency ω and the distance Δ, d_{jk} is the propagation delay for a phase between the two sensors j and k which can be computed using the average, dominant phase velocity of the phase in question (such as *Pn, Pg, Sn or Lg*). The formula states that the total observed spectrum is made up of the individual spectra of the sources plus all the cross-spectral contributions between all the possible distinct pairs of sensors. Given the fact that according to experience spectra of individual explosions are generally smooth, almost all of the modulation is caused by the cross spectral contributions, i.e. the second sum on the right side of (1).

In our simulations we have assumed, somewhat arbitrarily, the dominant phases velocities of 8.2, 6.0, 4.7 and 4.0 for Pn, Pg, Sn and Lg respectively. We have varied the decorrelation rates to study their effects for various types of geological situations. Seismic reciprocity as applied to regional signal decorrelation measurements at "small" arrays of a few km diameter implies that waveforms observed at a remote sensor from similar sources displaced over small distances will be similarly decorrelated. In order to optimize signal processing at regional arrays signal decorrelation was measured at the sites of small arrays in Scandinavia (Mykkeltveit et al. 1983). The results produced indicated that the degree of decorrelation increased in the order of Pn-Pg-Sn-Lg and that it also increased with increasing frequency. In this paper we shall assume a decorrelation function of the direction-independent form of $exp(-\alpha f\Delta)$, where α is a constant, f is frequency and Δ is the distance. The costant α will undoubtedly depend on the local geological heterogeneity of the particular area where the sensor or shot array is located and thus will be varied.

Applying Equation (1) to a simulated linear array demonstates that the underlying model can reproduce both the relative displacement of the nulls and maxima of the modulation patterns and the differences in the strength (peak-valley contrast) of modulation for the various phases (**Figure 4**). The shifts in modulation patterns for this case are umambiguous and azimuth-dependent.

A more realistic areal pattern we have simulated consisted of 5 rows of ten shots which the firing in the successive rows overlapped (**Figure 5**). Patterns of this kind were described by Chapman et al (1991). Similarly to observed data, differences in the frequencies of various features in the modulation patterns are small in this example, but the strength of modulation decreases strongly from Pn to Lg. The two-dimensional layout of this shot pattern makes the Doppler shifts complex and hard to see. This figure provides an explanation why shifts in modulation patterns are rarely seen in real observations although most shot patterns are generally large enough to produce significant propagation delays compared to the absolute time delays in a pattern.

RECOMMENDATIONS AND FUTURE PLANS.

Obviously spectral modulation patterns in regional arrivals contain information about the spatio-temporal layout of the shot arrays used. This information can potentially be used, in conjunction of independent information, to assess the sizes of shot arrays and in discrimination. Observation of modulation patterns from various directions from the source may enable us to infer the spatial layout of the shotarrays. Since this inversion constitutes a complex nonlinear estimation problem combinatorial optimization methods (such as genetic algorithms) may be used advantageously in such applications.

We find this part of our investigation nearly complete, during the future work on this project we shall concentrate on the other tasks described above.

Selected References.

Anderson, D.P. and B. W. Stump (1994), Utilization of near-source video and ground motion in the assessment of seismic source functions from mining explosions (Abstract). 16-th Annual Research Symposium, Phillips Laboratory- Air Force Office of Scientific Research, Thornwood Conference Center, Thornwood, N.Y., 7-9 September, 1994

Barker, T.G., McLaughlin, K.L. and J.L. Stevens (1993), Numerical simulation of quarry blast sources. Maxwell Laboratories, S-Cubed, La Jolla, CA. Technical Report prepared for Phillips Laboratory, Kirtland AFB, NM.

Baumgardt, D.R. and K. A. Ziegler (1988). Spectral evidence for source multiplicity in explosions, application to regional discrimination of earthquakes and explosions, *Bull. Seism. Soc. Am.* **78**, 1773-1795.

Chapman, M.C., Bollinger, G.A. and M.S. Sibol (1991), Spectral studies of the ealstic wave radiation from Appalachian earthquakes and explosions - Explosion source spectra modeling using blaster's logs. Virginia Polytechnical Institute, PL-TR-91-2231. Prepared for the Phillips Laboratory, Air Force Systems Command, Hanscom AFB, MA. ADA243956

Der, Z.A., Shumway, R.H. and A.C. Lees (1988), frequency domain coherent processing of regional seismic signals at small arrays.*Bull. Seism. Soc. Am.*, **78**, 326-338.

Der, Z.A., Hirano, M.R., Ziegler, K.A. and R.H. Shumway (1991), Broadband studies of seismic sources at regional and teleseismic distances. PL-TR-91-2059 (1). ENSCO Inc. Prepared for Phillips Laboratory, Hanscom AFB. ADA239201

Der, Z.A., Baumgardt, D.R., and R.H. Shumway (1993), The nature of particle motion in regional seismograms and its utilization for phase identification. *Geophys. J. Intl.*, **115**, 1012-1024.

Der, Z.A. and D.R. Baumgardt (1994), Issues in regional monitoring and mining operations for the presence of hidden nuclear tests. 1994 *ARPA CTBT Monitoring Technologies Conference. San Diego CA.*

Gitterman, Y. and T. van Eck (1993), Spectra of quarry blasts and microearthquakes recorded at local distances in Israel. *Bull. Seism. Soc. Am.*, **83**, 1799-1812.

Goldberg, D.E. (1989). *Genetic Algorithms in Search, Optimization & Machine Learning,* Addison-Wesley Publishing Company.

Kim, W.Y., Simpson, D.W. and P.G. Richards (1994), High frequency spectra and regional phases from earthquakes and chemical explosions. *Bull. Seism. Soc. Am.*, **84**, 1365-1386.

Mykkeltveit, S., Astebol, K., Doornbos, K.J., and E.S. Husebye (1983), Array configuration optimization. *Bull. Seism. Soc. Am.*, **73**, 173-186.

Smith, A.T. (1993), Discrimination of explosions from simultaneous mining blasts. *Bull. Seism. Soc. Am.*, **83**, 160-179.

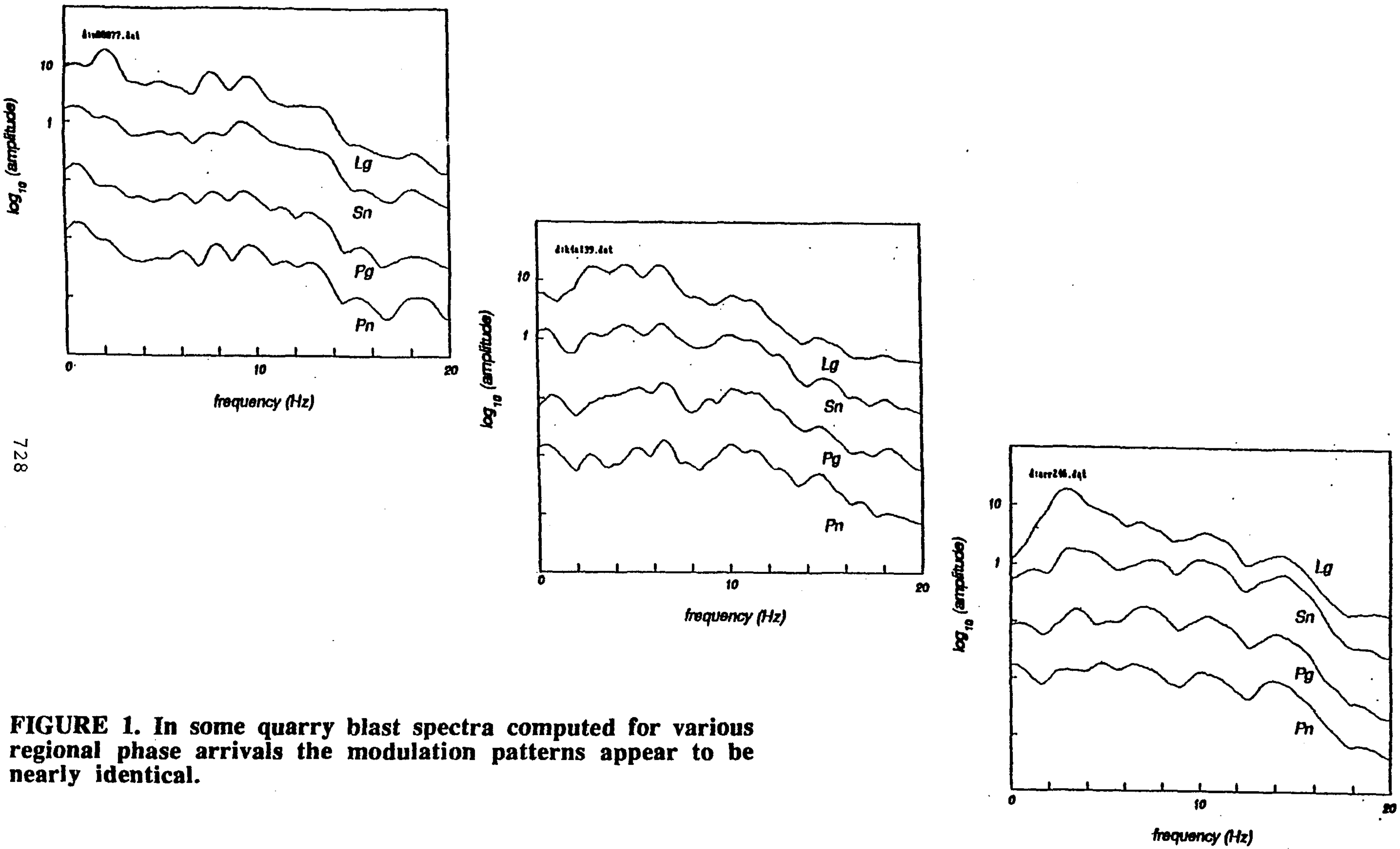
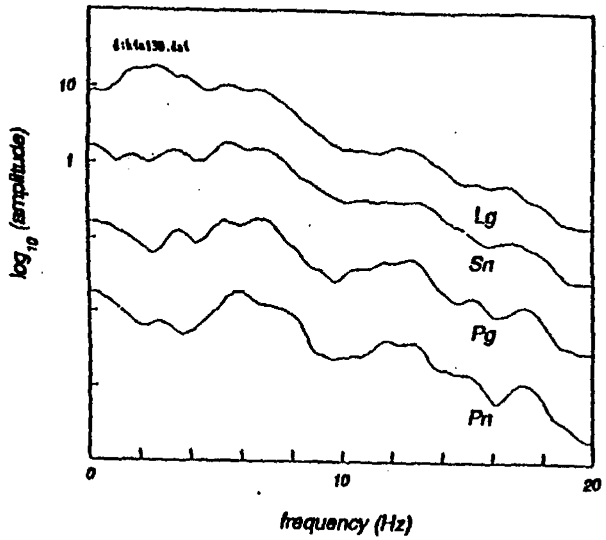
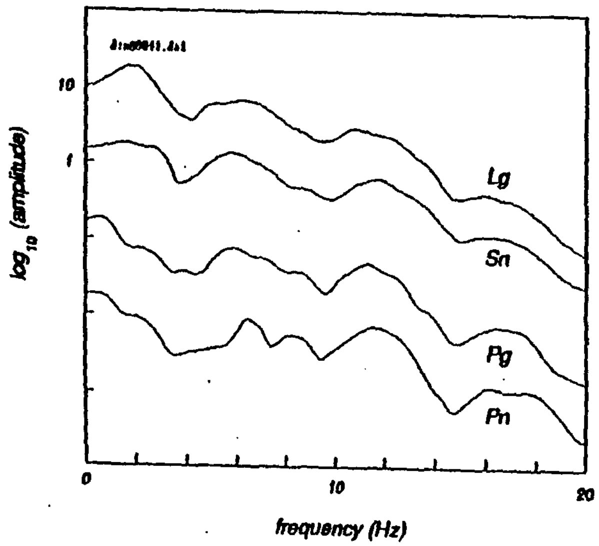


FIGURE 1. In some quarry blast spectra computed for various regional phase arrivals the modulation patterns appear to be nearly identical.





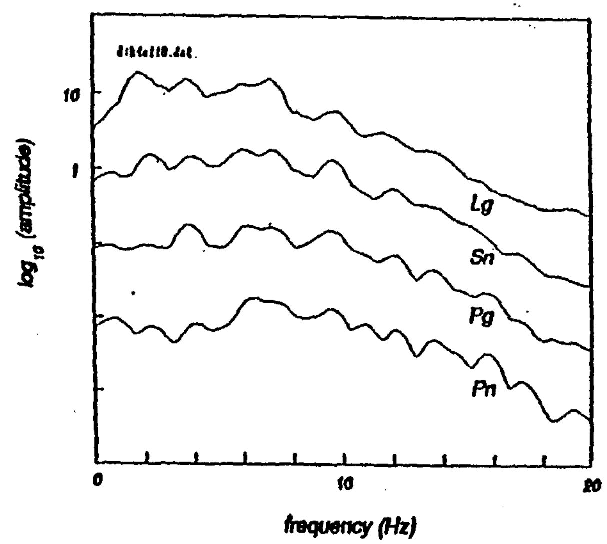


FIGURE 2. Most quarry blast spectra show differences in the strength of modulation (peak-valley contrast) among the various regional arrivals. The modulation tends to decrease from Pn to Lg and increasing frequency. We explain this with the decorrelation of shot waveforms with distance, frequency and the type of phase.

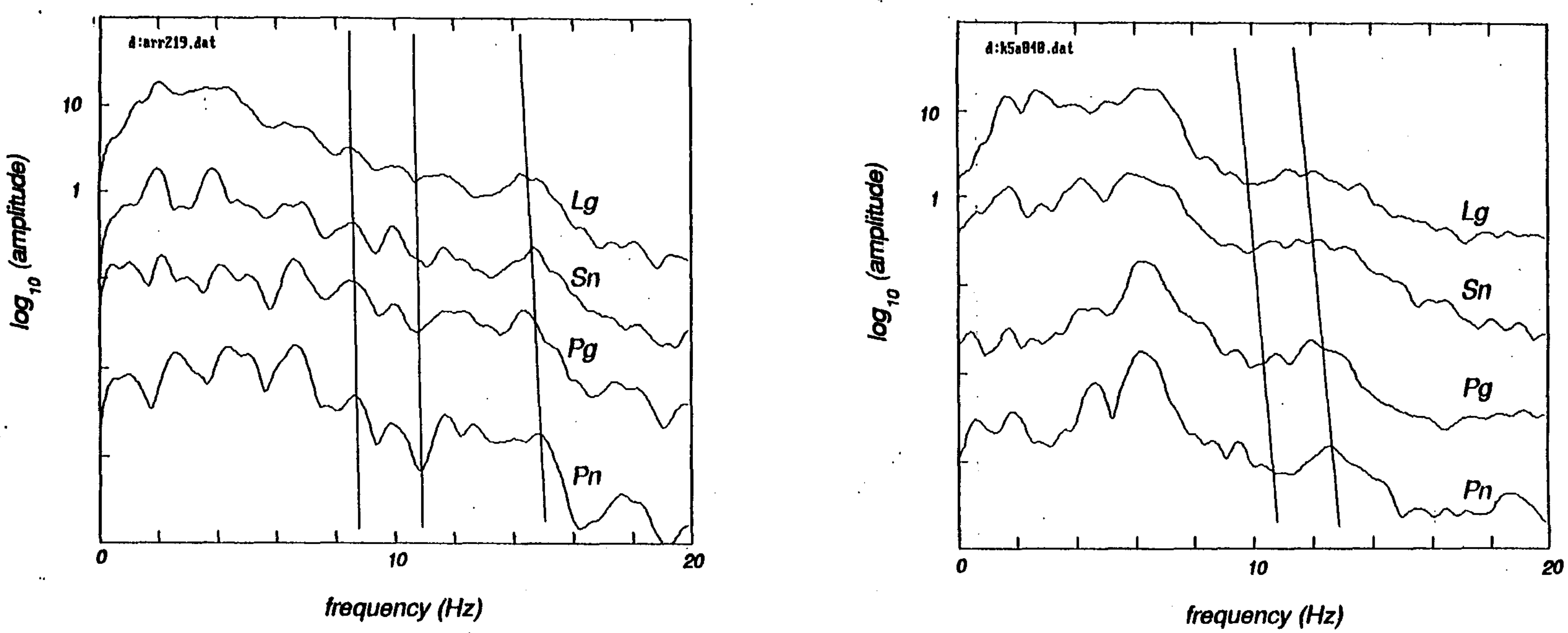


FIGURE 3. Some spectra show displacement (scaling) of modulation among the various phases as indicated by lines. Propagation delays (Doppler effect) are the probable explanation.

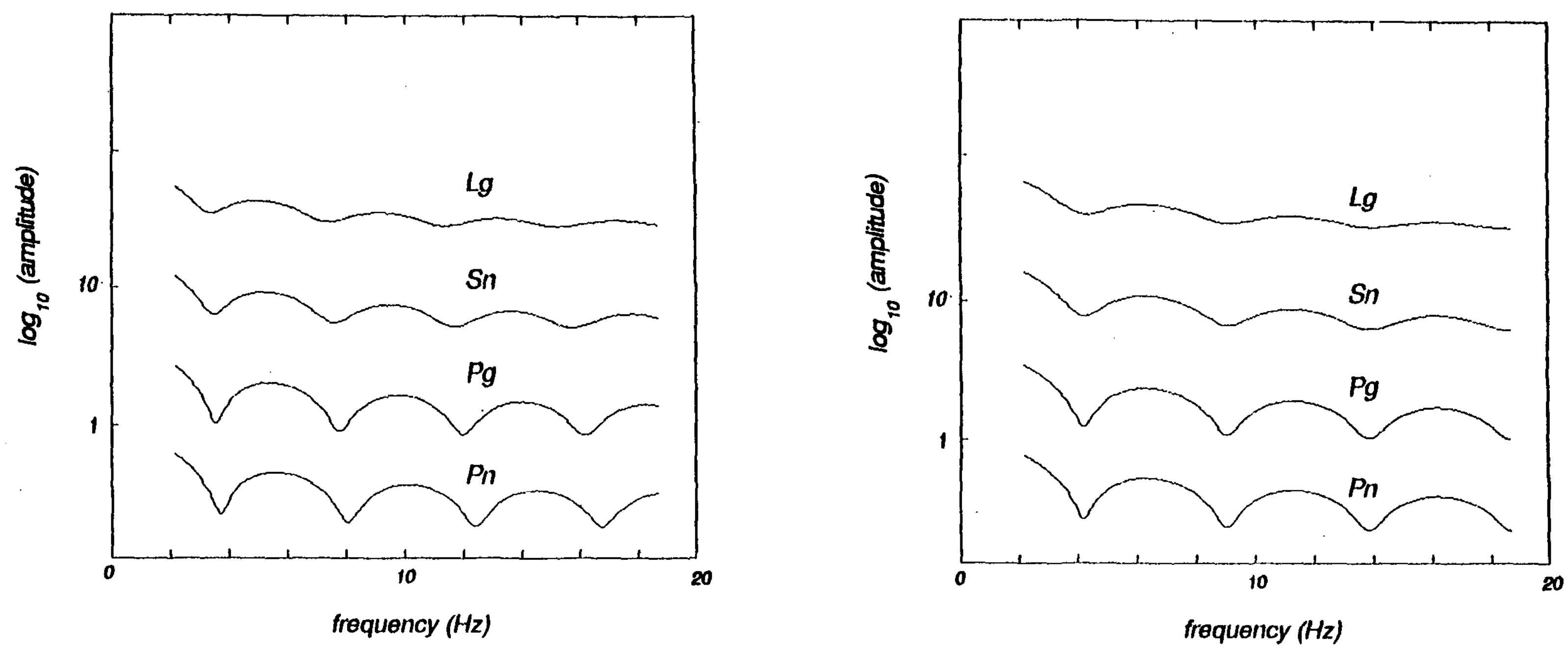


FIGURE 4. Simulated spectral modulation patterns for a 10 element linear shot array with spacings of 20 m and and intershot delays of .02 seconds. All spectra show a diminution of modulation intensity from Pn to Lg, but depending on the azimuth the features in the modulation shift to the left when the successive shots move away from the observer (left), and remain the same when the distances to the various shots are constant (right).

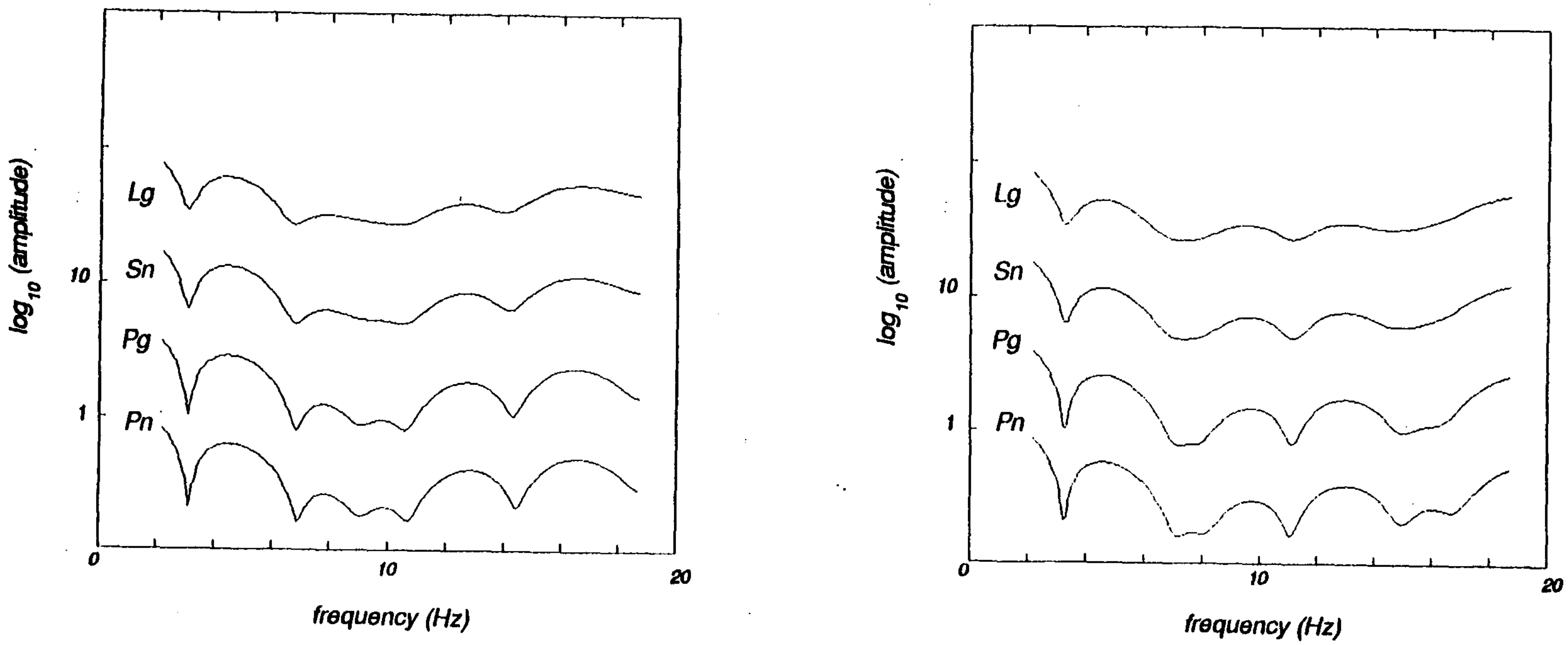


FIGURE 5. Simulated spectral modulation patterns for a 50 element areal shot array with row spacings of 10 m, 10 shots in a row spaced at 10 m. The intershot delays in each row are .01 seconds and the delay between rows is .05 seconds. All spectra show a diminution of modulation intensity from Pn to Lg, some of the modulation features show weak indications of small shifts. The left panel depicts spectra for the direction perpendicular to the rows, the right panel in the direction of the rows. The shooting sequences (of rows and columns respectively) move away from the observer. Shifts in features are weak or absent.